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A Computational and Experimental Methodology to Measure Cervical Spine Shear Mechanics

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ABSTRACT

While spinal shear characteristics are necessary to accurately model the spine, the response of the cervical spine to pure shear displacement is not well understood. Previous experimental studies have evaluated the spine in shear using variable loading environments, load magnitudes, and by testing both single and two functional spinal unit (FSU) constructs. In reviewing these research efforts, we performed a number of experiments and computational studies aimed at critically investigating the shear mechanics of the spine. Non-destructive anterior, posterior, and right lateral shear displacements were applied to fifteen 2-FSU baboon spinal segments. Four of those segments were then further disarticulated and tested to failure as single FSUs. The load-displacement profiles for each of these tests revealed complex kinematics and variable tissue stiffness values in different loading directions. Further, we identified appropriate loads for future non-destructive testing and compared the loading environment and resulting mechanics of one versus two FSU segments. This study revealed that the use of a 2-FSU construct in a pure shear loading apparatus did not place each FSU in pure shear but rather a complex shear and bending environment. In these tests, the stiffness of each FSU in 'shear' could be approximated as twice the stiffness of the entire 2-FSU segment. However, we found the most reliable test configuration for the non-destructive mechanical characterization of spinal tissues in shear to be testing single FSUs in pure shear loading up to 100% body weight.

INTRODUCTION

Cervical spine shear mechanics have not been well characterized, especially in the pediatric age range, despite their importance to modeling and anthropomorphic test dummy performance for injury prevention. Previous studies have attempted to measure the effect of shear loading using both single FSU (Moroney, 1988; Panjabi, 1986) and 2-FSU segments (Shea, 1991); however these tests were often performed at low loads (<70-N), and were not limited to pure shear displacements (Moroney, 1988; Panjabi, 1986). This study evaluated these parameters using both experimental and computational methods.

A number of experimental methods have been used by researchers to examine the shear mechanics of the spine. These studies applied shear loads accompanied by bending moments or tensile forces (Moroney, 1988; Panjabi, 1986). Further, most of the early studies were performed at loads below the physiologic functional range. Shea et al., overcame these limitations, and performed a study in which they determined that the stiffness of a 2-FSU segment could be approximately doubled to yield each individual FSU stiffness. They also found no significant difference in stiffness between anterior and posterior shear, or the middle (C2-C5) and lower (C5-T1) cervical spine(Shea, 1991). Another study has shown that the intervertebral disc is the largest contributor of stiffness under anterior shear loading, bearing up to 70% of the ultimate shear load (Yingling, 1999), suggesting that the remaining soft tissue takes up the other 30%. This study emphasized the different contributions of the spinal tissues whereby leading us to believe that different shear loading directions will have varying mechanical responses.

The goal of this study was to examine the experimental shear response of the cervical spine and evaluate the following factors: i) isolated pure shear loading, ii) physiologic shear load levels, and iii) the use of the 2-FSU construct to predict single FSU shear mechanics. Further, this research effort utilized idealized computational models to aid in these efforts.

METHODS

Specimen Preparation.

Five, fresh-frozen cadaver baboon spines, obtained through the Washington Regional Primate Research Center, were used in this study. These specimens were euthanized for unrelated short-term (6-8 week) vascular research projects which should not have affected musculoskeletal properties. All five specimens were males age 6.6 ±0.9-human equivalent years (Ching, 2001) to preclude gender and age differences. Each specimen was inspected for previous injury or spinal pathology and dissected free of all musculature leaving the full intact osteoligamentous cervical spine. The cervical spine specimen was then disarticulated into three 2-FSU segments: Oc-C2, C3-C5, and C6-T1. Coronal and sagittal plane radiographs, as well as axial computed tomographs (CTs), were taken of each specimen to make gross measurements and define specimen skeletal maturity (age). In preparation for testing, the free ends of each 2-FSU specimen were wired and embedded in poly-methylmethacrylate. Immediately after dissection, each specimen was hydrated, wrapped in towels, sealed in a plastic bag, and frozen at –20°C to preserve their mechanical properties (Panjabi, 1985).

Instrumentation.

We have developed a shear-testing apparatus that is unique from techniques used in the past as it provides a pure shear displacement to the spine. As a result, more accurate measurements of shear properties and mechanical thresholds are obtained. Previous studies of spinal shear characteristics were performed in such a way that the resulting loading/motion was actually one of bending (Moroney, 1988; Panjabi, 1986; Panjabi, 1975). These tests were conducted by loading one end (free end condition) of a spinal segment in shear while the other end was held fixed. These specimens were allowed to displace angularly which resulted in a loading profile that included a shear component and a bending moment component, which increased with angular displacement.

Our shear-testing apparatus (Figure 1) eliminates angular displacements and allows a specimen to displace only in the axial and shear directions, applying pure shear through a spinal segment. Each of the potted ends of the specimen is secured to a ball-bearing carriage, and the carriages run along separate linear tracks (Thomson Industries, Inc., Part 2DA-12-K0A-L8), which are positioned orthogonal to one another. This fixturing places the spine horizontal, enabling the MTS actuator (Model 858 Bionix, MTS Corp., Eden Prairie, MN) to apply a shear load to the specimen with axial displacement of the actuator. While the superior end of the specimen is loaded in anterior-posterior or lateral shear, the inferior end is free to move only axially (orthogonal to the actuator), maintaining pure shear. We are able to quantify the displacements, loads, and moments 'seen' by the specimen during loading through a combination of LVDTs and load cells. The MTS LVDT measures the movement of the superior end in the shear-loading direction while a second LVDT measures the axial movement of the inferior end. A six-axis load cell, attached inferiorly, measures the forces and moments experienced by the specimen during loading. An additional load cell measures the force applied to the superior end of the specimen to control the shear forces. Video analysis (WinAnalyze software) enabled the verification of the LVDT displacements and the measurement of other displacements such as the middle body of a 2-FSU specimen.

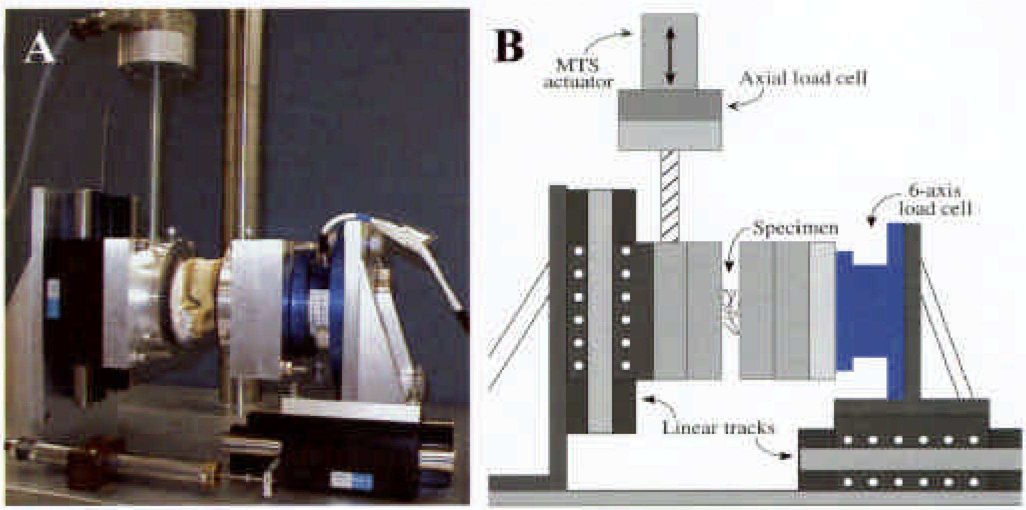

Figure 1. Shear testing apparatus. (A) Shear testing device attached to the MTS with a dummy specimen in place. (B) Side view schematic diagram of the experimental set-up with the major components labeled.

Experimental Procedure.

Each of the fifteen 2-FSU segments was tested non-destructively at 0.05-mm/sec to 5.0-mm/sec up to 100% body weight (approximately 75-N) in anterior, posterior, and right lateral shear. These non-destructive tests included five haversine loading curves at 0.1-mm/sec (quasi-static) followed by three triangle wave displacement inputs of 0.05-mm/sec, 0.5-mm/sec, and 5.0-mm/sec. Finally, a stress relaxation test was performed with a step to 100% body weight (at 100-mm/sec) and held for 180-sec.

Two of the cervical spines were used to examine the relationship between the stiffness of individual and multiple FSU segments in shear loading. The C3-5 and C6-T1 segments of these specimens were further disarticulated into single FSU segments, yielding one test specimen for each level: C3-C4, C4-C5, C6-C7, C7-T1. An identical shear-loading regime was applied to the single FSUs in all three shear-loading directions. Each of those four specimens was then tested to failure at 0.1-mm/sec in a shear loading direction chosen at random (Table 1).

Table 1. Two 2-FSU test specimens were dissected into single FSU segments and tested nondestructively and then to failure. This table summarizes the direction of loading to failure.

Level	Failure Test Direction
C3-4	Posterior Shear
C4-5	Anterior Shear
C5-6	Right Lateral Shear
C6-T1	Posterior Shear

All of these data were collected at 200-Hz using a LabVIEW data acquisition board (PCI-6071E, National Instruments™, Austin, TX) on a personal computer (E-5200, Gateway™, Sioux Falls, ND). The 200-Hz sensor data was then compared and synchronized with the video data which was collected at 30-Hz. Since this study included very small sample sizes, no statistical analyses were performed. It was the intent of this research effort to elucidate initial parameters and variances for future sample size calculation and statistical analyses.

Computational Procedure.

Idealized lumped parameter and finite element models were created to simulate the 1-FSU and 2-FSU experimental shear tests. The goal of this effort was to re-create the experimental kinematics of each system (1-FSU and 2-FSU) so that parametric analyses could be performed identifying the most significant structural shear characteristics to guide future experimental testing.

The idealized FE model was created in LSDYNA (v.960, Livermore Software Technology Corp. Livermore, CA) which consisted of a 66-mm cylinder with a 14-mm radius; the cylinder was sectioned into layers with three 12-mm vertebral bodies and two 10-mm discs. Metal plates were modeled at both ends of the cylinder. The bones are considered to be rigid, while the metal plates (modulus = 210E3- N/mm^2, Poisson's ratio = 0.30) and disc annulus fibrosis (modulus = 2.83-N/mm^2, Poisson's ratio = 0.45) are elastic. The applied load and the boundary conditions mimic the experimental setup. Thus, this model provides us the ability to computationally determine the shear stiffness of a 2-FSU construct as well as calculate the shear stiffness of its individual FSUs. This FE model was also constructed in a single FSU version for comparison purposes. Therefore, the mechanics of a single FSU should be the same in both the 2-FSU and 1-FSU tests and differences between these tests will be able to be elucidated.

Further, we created single and 2-FSU lumped parameter models (Working Model 2D, MSC Software, San Mateo, CA) in which the intervertebral joints were approximated by tensile and shear springs. The spring stiffnesses were derived from experimental single FSU tests conducted in our lab (Ching, 2001). These models were also used to evaluate the single versus 2-FSU shear response.

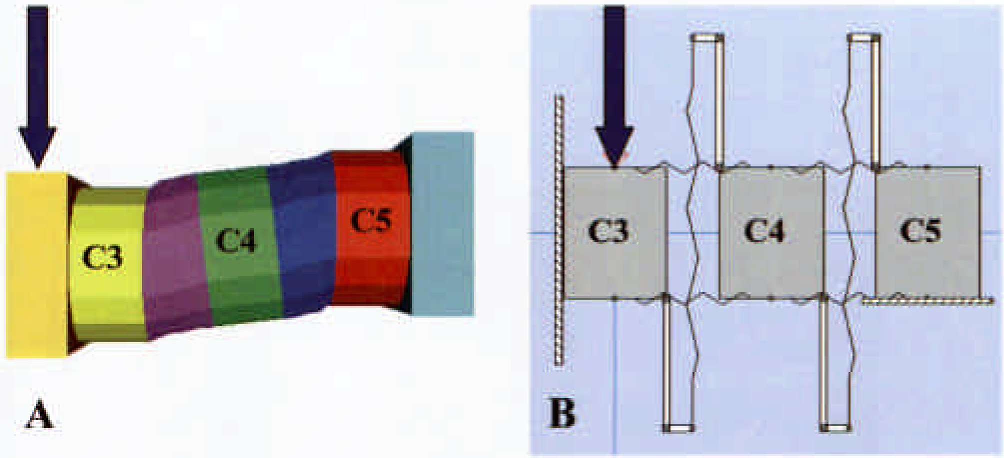

Figure 2. Computational modeling efforts of 2-FSU constructs in shear. (A) The finite element model shown here displaced with a 100-N load and the resulting intervertebral disc displacements and rotation of C5. (B) The lumped parameter model had similar loading to the FE model (shown here unloaded) and also comparable displacements.

RESULTS

The non-destructive testing demonstrated differences in stiffness by loading direction but in general very comparable shear results. Evaluation of the variable loading rate tests demonstrated hysteresis energy similar between loading rates. The stress relaxation response of each specimen exhibited a typical viscoelastic relaxation response in each loading direction. A haversine loading protocol enabled the collection of non-destructive 2-FSU data from which the stiffness of the construct was calculated as the slope of the linear portion of that load-displacement curve. Figure 3 depicts the mean stiffness values measured for the 2-FSU segments for each level of the cervical spine tested and in each loading direction. These data do not appear to be dissimilar when comparing loading direction or cervical level. Further, the mean shear stiffness over all of the levels and loading directions was 54 ±8-N/mm.

The 2-FSU segments also exhibited large angular displacements of the middle vertebral body ($\approx 6^{\circ}$) indicating that once the middle body displaced angularly, there was no longer a pure shear displacement in each intervertebral disc. Thus, the 2-FSU test does not apply pure shear throughout the experiment. Further, computation of the shear component for each FSU was untenable without knowing the internal moment generated in the middle vertebral body. Therefore, we sought to compare the 2-FSU construct to the single FSU from the same specimen in an attempt to understand the shear versus bending components in our 2-FSU testing.

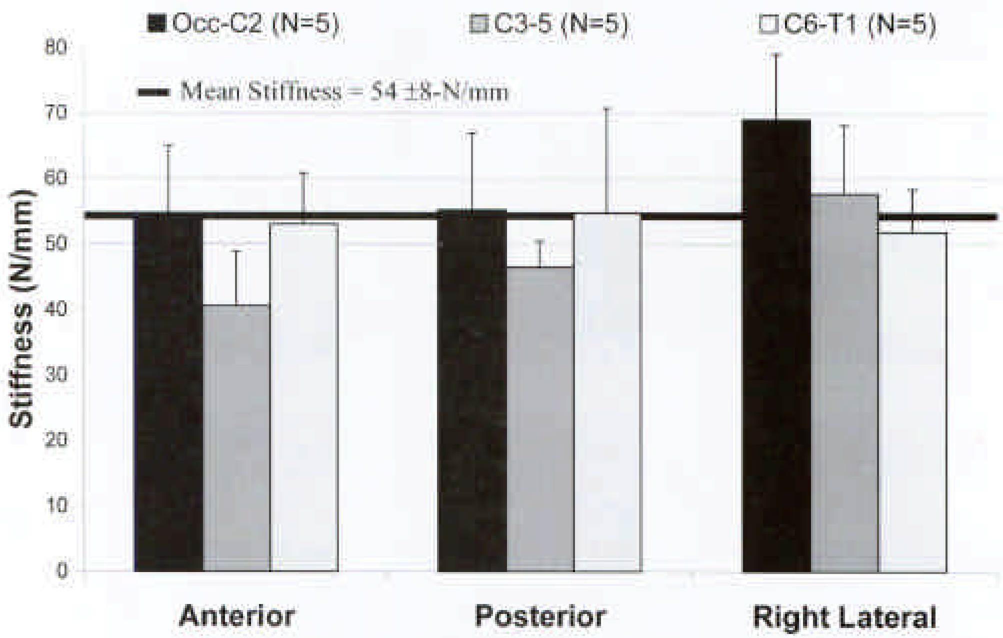

Figure 3. 2-FSU non-destructive stiffness data for each cervical segment in each loading direction. This plot illustrates the calculated stiffness from the load-displacement curve of each non-destructive test. Each bar represents the mean and standard deviation of 5-specimens and the dark line represents the mean of all (direction and level) 2-FSU experiments equal to 54 ±8-N/mm [N=45].

Single FSU testing revealed similar non-destructive load-displacement patterns; however, the failure data provided the most interesting results. The load–to-failure tests were performed over various loading directions and for different cervical spine levels. Each load-displacement plot had a characteristic toe region followed by a linear region up to failure. While the single FSUs reached varying ultimate loads, three of the four specimens failed at a displacement between 6-7-mm (Figure 4). The posterior and right lateral tests had similar loading curves and stiffness values, with a mean of 88-N/mm. The anterior test gave a higher stiffness value than the others of 125-N/mm. It also had a much larger toe region than the other tests, as it did not reach the functional range until over 100% body weight. The mean stiffness of these four tests in various loading directions and cervical levels was measured to be 98 ±20-N/mm.

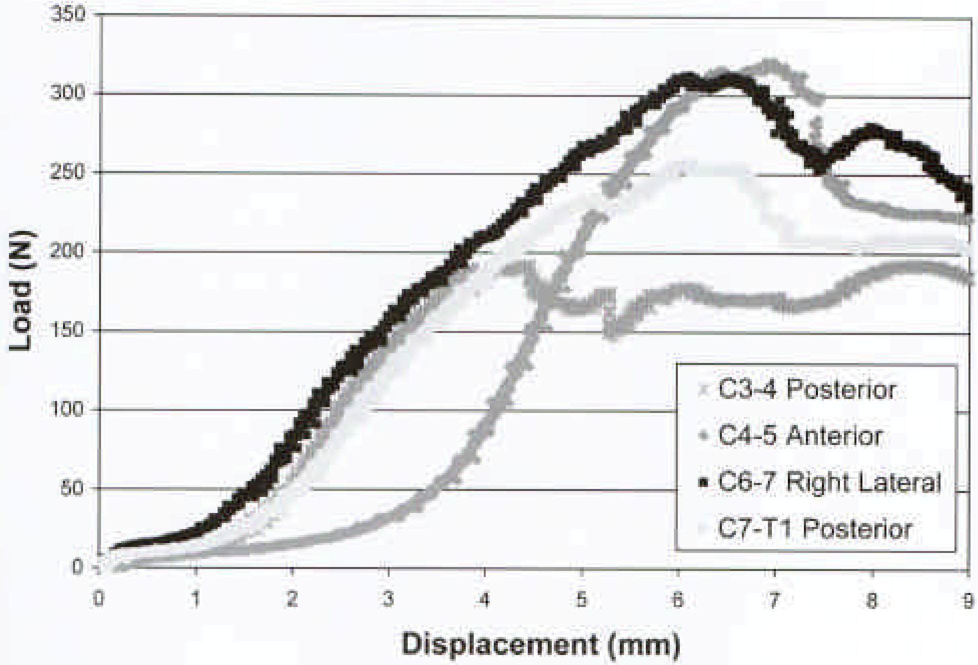

Figure 4. Single FSU failure load-displacement curves for each loading direction at various cervical levels. Note that the stiffnesses of each of the posterior and left lateral tests are very similar and the anterior test has a large toe region with a steeper stiffness value. The mean stiffness of these four experimental tests is 98 ±20-N/mm.

The results from the computational models are consistent with those from the 2-FSU experimental tests. The displacements measured in both models were similar and accounted for twice the displacement of the superior body compared with the middle body and the middle body rotating approximately 6-degrees. The finite element model results demonstrated C3 displacing 6.4-mm in the shear direction, C4 (middle body) displacing 3.2-mm in the shear direction and rotating 6.5-degrees, and C5 moved 0.144-mm axially. The overall shear stiffness of the 2-FSU construct was 15.6-N/mm, while the shear stiffness of the top and bottom FSUs were 31.1-N/mm. The lumped parameter model resulted in very similar shear displacements in response to a 100-N input. The C3 body displaced twice the amount of the C4 body in shear and the C4 body rotated 5.9-degrees. The shear stiffness of the 2-FSU construct was 21.5 N/mm, while the shear stiffness of the top FSU was 54.8 N/mm and the bottom FSU was 51.9 N/mm.

The results of the single FSU computational tests for both models revealed that a 100-N load would result in smaller displacements across one disc than those measured for the 2-FSU test. These displacements were 20% less for the lumped parameter model of a single disc (C3-4 for example) compared with that same disc in a 2-FSU loading environment.

DISCUSSION

This project was directed towards understanding the shear mechanics of the cervical spine through experimental and computational modeling efforts. We aimed to evaluate the following parameters: i) isolated pure shear loading, ii) physiologic shear load levels, and iii) the use of the 2-FSU construct to predict single FSU shear mechanics. This discussion will examine these parameters and suggest a course of action for further experimental and computational research.

Shear Loading

Our shear testing device generated pure shear displacements in the cervical spine and measured the resulting load response. Hence, the data collected in this study can be incorporated into physical (anthropomorphic test dummy) and computational models as pure shear characteristics. For single FSU testing, our experimental and computational modeling efforts demonstrated comparable stiffness values in response to similar shear load application. Thus, pure shear loading of the cervical spine is preferable when generating shear characteristics for modeling efforts.

Cervical Spine Shear Load Levels

The results from the 1-FSU failure tests indicated that our non-destructive load levels for the posterior and right lateral experiments were appropriate for examining the functional range. Unfortunately, anterior shear testing in the physiologic (linear) range appears to be at load levels greater than 100% body weight. Thus, future experimental work should examine the functional range of cervical spine shear mechanics to above 100% body weight for accurate determination of material properties.

Single FSU Prediction from 2-FSU Experiments

Comparison of the 2-FSU and 1-FSU generated stiffness values provides on average a similar relationship to that found by Shea et al. (Shea, 1991). A measured mean of 98 N/mm for the single FSU tests is approximately twice the mean of the 2-FSU segments (54 N/mm). While this provides a simple prediction method for single FSU mechanics from 2-FSU tests, nuances in the mechanics due to loading direction and cervical spine level cannot be appreciated.

Most of our data fit this 50% model; however, one of the C3-5 segments tested in posterior shear represents a case which requires further thought. The C4-5 stiffness (measured while testing to failure) of this segment was 81-N/mm as determined by the 1-FSU test. That same segment, tested as part of the 2-FSU C3-5 construct, had a stiffness of 128-N/mm, as determined from video analysis. The superior FSU (C3-4) of this 2-FSU segment had a calculated stiffness of 77-N/mm. The single FSU test does not allow rotation of the middle body and thus, the stiffness corresponds to only soft tissue mechanics between the two bodies. The 2-FSU test allows rotation of the middle body and thus bony interaction of the middle body with the inferior body throughout the test. This bony interaction might explain why the inferior segment has a larger stiffness (128-N/mm) compared with the superior segment (77-N/mm) which may not have bony interaction. While this is merely a case study (N=1), it suggests that the 2-FSU kinematics of each of the different loading directions (anterior, posterior, or lateral) may be different and provide for inaccurate estimation of single shear mechanics.

The single FSU and 2-FSU computational models also show dependence on spinal kinematics for accurate prediction. The 1-FSU models demonstrated smaller displacements across a single level than the 2-FSU models, and that demonstrates the differences in the loading environment of each of these two tests. Our experimental stiffness results compared well with the modeling results for a single FSU test. Unfortunately, the comparison of the 2-FSU experimental and computational efforts did not give similar results and lead us to question the simplicity of our modeling efforts.

Future experimental testing on a series of specimens both single and 2-FSUs will enable us to fully characterize cervical spine shear mechanics. The results of this study make it imperative that we test in pure shear up to load levels above 100% body weight to obtain single FSU shear mechanics from non-destructive tests. These data will help to improve both the biofidelity of anthropomorphic test dummies and material property values for computational modeling whereby enhancing injury prevention.

CONCLUSION

This experimental study in cervical spine shear mechanics predicted a stiffness ratio of 1–FSU: 2–FSU as being approximately equal to 2. Both finite element and lumped parameter models predicted this relationship as well, and demonstrated similar kinematics for the 2–FSU segments. Experimental results suggest interactions which were not modeled, such as that of the facets, may confound 2-FSU results. Therefore, single FSU experimental tests in pure shear up to 100% body weight are preferable to measure the physiologic shear mechanics of the cervical spine.

ACKNOWLEDGEMENTS

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DISCUSSION

PAPER: **A Computational and Experimental Methodology to Measure Cervical Spine Shear Mechanics**

PRESENTER: ***Susan Hertsted, University of Washington.***

QUESTION: *Guy Nusholtz, Daimler Chrysler*

Your stiffness or your forced deflection curves or shear deflection curves look very non-linear, what are you using as stiffness because now you've got a single valued parameter?

ANSWER: You're talking about for actual experimental tests here, this right here?

Q: Like that one, yes. Particularly if you look at the yellow there is no section in there where one would want to define the stiffness. So are you picking a point?

A: No. We are actually taking the linear region as seen in this anterior test, the gold line. We're taking the linear region here. As we suspect it gets out of the toe region maybe about 75 or 100 Newtons there.

Q: If you're going to use that stiffness in the model you are going to kind of fool yourself. Have you thought about trying to come up with some sort of constitutive function that gives you a better estimate of what those curves might be?

A: To include the toe region?

Q: To include the toe region. If you look at the green ones you've got flexing this way, you look at the yellow ones it is going this way. You have a characteristic curve, which looks like you might not want to model that with a linear system. If you draw a straight line, if you do it the way you're doing it, then at zero either have some funny force or zero deflection or at some displacement you've got zero force?

A: Right. This is something we have considered, but we haven't actually gotten into that yet.

Q: *King Yang, Wayne State University*

You mentioned there is significant rotation in the middle spine and yet you say you test one FSU is better than two. So how do you account for this rotation?

A: Well, that's what we are trying to address here is whether we can determine the single FSU values from that two FSU test where we do get rotation of the middle body. So, we're trying to actually take out that rotational component. That's where we came up with the general approximation to double the stiffness of that two FSU to get the one FSU stiffness. However, we see interactions obviously, that's why we get the rotation of the middle body that would cause different loading directions to actually have different stiffnesses which leads us to believe that we need to come up with a better model and perhaps look at more of these single FSU tests.

Q: Personally, if this is the real phenomenon, I would test two, or even three or four FSU rather than one?

A: Right. Thank you.